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CALCULATION OF THE AERODYNAMIC CHARACTERISTICS OF A TWISTED JET

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Foreign Technology Division
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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

CALCULATION OF THE AERODYNAMIC CHARACTERISTICS OF A TWISTED JET

R. B. Akhmedov and T. B. Balagula

An analysis of the experimental works on a twisted jet and an observation of various theoretical schemes have shown that the known calculation methods permit one to describe a twisted jet in the areas where the initial geometry of a swirl vane has no effect. Meanwhile the area of a flow of a twisted jet near the nozzle depends considerably on the initial conditions. Based on the analytical calculation methods, which permit the consideration of the geometry of a swirl vane, of primary interest is the method of equivalent problem of the theory of heat conductivity, developed by L. A. Vulis. The applicability of this method was confirmed for a whole number of direct-stream fluxes; however, the data which could be used to evaluate its applicability in the calculation of twisted jets were plainly insufficient. The method of equivalent problem of the theory of heat conductivity was first used in work [5] for calculating velocity fields of a single twisted jet flowing from a helical tangential twist vane with the twist parameter value of 2.07 In this case, instead of the usually used value of dynamic pressure ρu^2, the value of a total pulse was introduced into the calculation scheme of the method, which included the excess static pressure ($H = p_{ст} + \rho u^2$), determined by the equation of heat conductivity

$$\frac{\partial H}{\partial \xi_H} = \frac{\partial^2 H}{\partial y^2} + \frac{1}{y} \cdot \frac{\partial H}{\partial y}, \tag{1}$$

which, with an arbitrary profile H given in the form $H = H_0(y)$ and boundary condition $\frac{\partial H}{\partial y} = 0$ with $y = 0$ and $\frac{\partial}{\partial} \to 0$ with $y \to \infty$, permits a solution in the form

$$H(\xi_H, y) = \frac{1}{2\xi_H} e^{-y^2/4\xi_H} \int_0^\infty H_0(\rho) e^{-\rho^2/4\xi_H} I_0\left(\frac{y\rho}{2\xi_H}\right) \rho \, d\rho. \tag{2}$$

The basis for the introduction of H into the calculation scheme of the method of the equivalent problem is in the fact that, in the case of a nonisobaric flow (and it is precisely to this class of fluxes that the twisted jets belong), it is not the flow of pulse ρu^2 that is the remaining value, but $\int_0^\infty Hr \, dr =$ $=$ const, i.e., H is the remaining value in all cross sections of the jet.

The calculation results for field H according to (2) and H values obtained by the test data [3] have shown a satisfactory agreement for a twisted jet flowing from a helical tangential swirl vane with a single value of the twist parameter. For a more extensive verification of the applicability of this method, a study was made of the possibility of calculating these jets using the various techniques for twisting these jets.

This work presents the results of the experimental and calculation study of a twisted jet flowing from an axial-flow swirl vane of the blade type and from an axial-tangential blade and helical swirl vanes. We present the basic structural parameters of the studied swirl vanes and the value of twist parameters n, determined by the formulas of work [1].

1) Axially bladed register A (diameter, in mm, of neck (d) - 200, bushing (d_0)-50, d_0/d-0.25, blades-16)

Blade setting angle α, in degrees	Intensity of twist n
20	0.35
30	0.55
40	0.79
50	1.13
60	1.65

2) Axially tangential blade register AT (diameter mm: neck (d)-200, bushing (d_0)-70; d_0/d-0.35)

Angle between the outlet blade edge and the axis of the cylindrical channel β, in degrees	25	25	25	45	45	45
Angle between the blade and the tangent to the internal periphery of twisting, α, in degrees	45	30	20	45	30	20
Intensity of twisting n	0.38	0.64	0.80	0.63	0.93	1.35

3) Helical register Y (neck diameter d-200 mm)

Width of tangential inlet a, in mm	128	85	128	66	100
Length of tangential inlet b, in mm	512	340	256	265	200
Intensity of twisting n	1	2	2	3	3
a/d	0.64	0.425	0.64	0.33	0.50
b/d	2.56	1.70	1.28	1.325	1.0
a/b	0.25	0.25	0.50	0.25	0.50

The calculation for the fields of total pulse H was made, just as in [5], according to formula (2) based on the experimentally obtained initial profiles of complete pulse H. In accordance with the general method of the equivalent problem of the theory of heat conductivity, relationship $\xi(x)$ is determined by comparing the theoretical and experimental data with a certain value of the transverse coordinate y. If this comparison is usually made when y=0, i.e., on the jet axis then, in this work, relationship $\xi_H(x)$ is determined according to the coincidence of the values of positive maximums of the experimental and theoretical profiles of H (Figure 1). It turned out that, assuming the invariance of the second coordinate $\eta=y$, the calculated curves have shown regular shift in the calculation maximum from the experimental toward the area away from the jet axis on the sections close to the nozzle (Figure 2) in the case of strong twisting of the jet. The following transformation was introduced to calculate this regular displacement:

$$\eta = y + a. \qquad (3)$$

Value a is selected such as to combine the calculation and this experimental maximums.

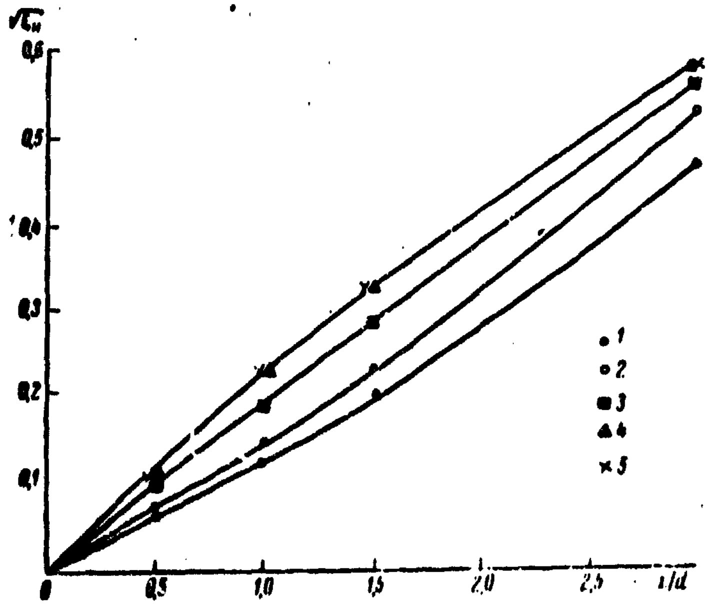

Figure 1. Dependence $\sqrt{\xi_H}=f(x)$ for a twisted jet flowing from blade register A. Value of angle α, in degrees: 1 - 20; 2 - 30; 3 - 40; 4 - 50; 5 - 60.

Figure 3 shows the form of fields H in an axial register after transformation (3); experimental fields H have two special features:

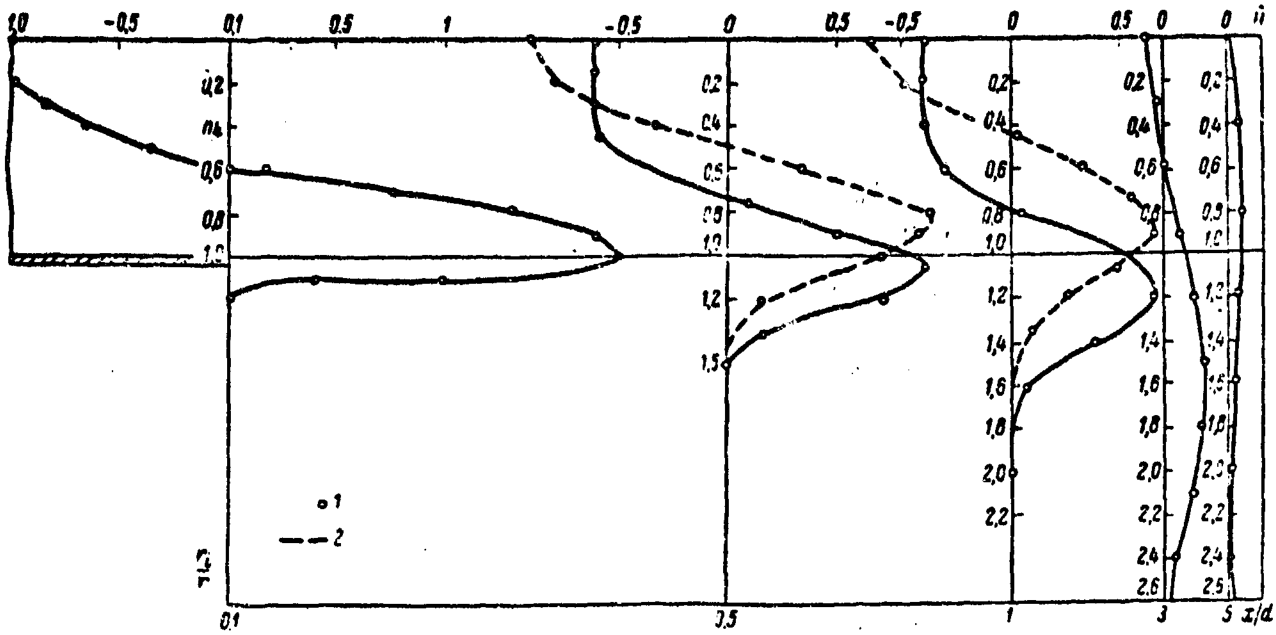

Figure 2. Field of total pulse H in the twisted jet flowing from register A at α=40°. 1 - experimental data; 2 - calculated, using the method of an equivalent problem without introducing the transformation of the displacement.

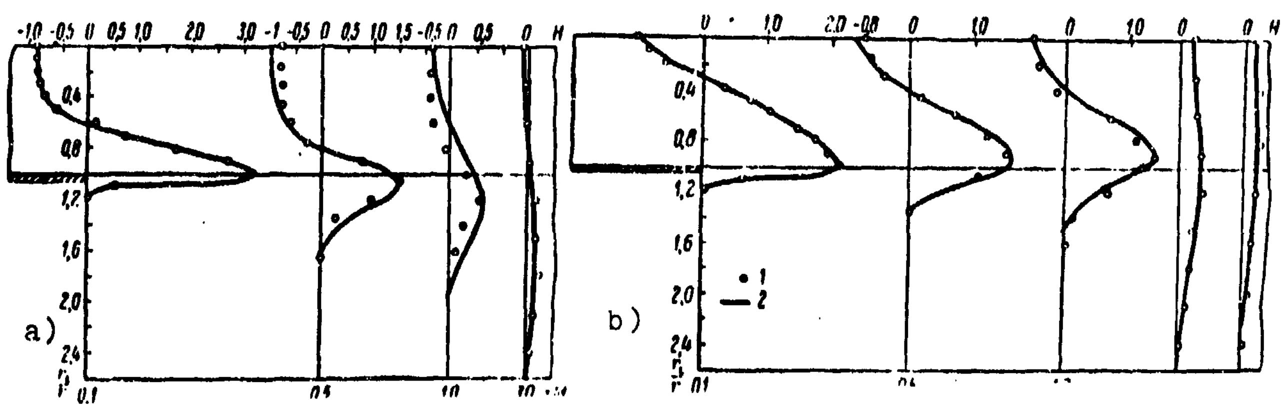

Figure 3. Field of total pulse H in a twisted jet flowing from register A. Values of α, in degrees: a) 40, b) 30, 1 - test, 2 - theoretical data.

first, maximum H is displaced away from the axis as it moves away from the nozzle and, with an increase in twist parameter n, this displacement increases; second, with large values of the twist parameter the H retains a certain constant negative value in the near-axis region in each section, which diminishes in absolute

values in proportion to the distance from the opening.

From Figure 3 it is evident that the calculation curves in the area of positive values of H are in relatively good agreement with the experimental data. In the area of the negative H values, the agreement between the theory and experiment was not obtained even after the introduction of transformation (3). Figure 4 shows the calculation results for the H fields for helical and axial-tangential swirl vanes [2]. Just as in the case of an axial feed the coincidence in the near-axial zone cannot be considered satisfactory.

An analysis of the obtained materials shows that the nature of rotation of the air flow has a considerable effect on the coincidence of the theoretical and experimental data: a better coincidence is obtained for a helical register whose field of total pulse, especially at small twistings, is close in form to field H for the axial-flow blade register. It is interesting to note that in the volute maximum H in the experiment is displaced to the jet axis (despite the fact that the twist is relatively large, n=1). In this case we did not have to introduce transformation (3). Evidently this nature of field H in the helical register can explain the satisfactory agreement between the theory and the experiment, obtained in work [5]. When n=1 the coincidence between the theory and experiment in the region close to the axis is worse (Figure 4, 1, a). Such a divergence of data with work [5] can be explained by the fact that, in addition to n the nature of the flow field (quasi-solid or potential) is affected by the value of the ratio of the width of the inlet connection across the axis of the burner to the length of the inlet connection along the axis of the burner ($\frac{a}{b}$). The region of quasi-solid rotation which is characteristic for the axial-type register with the blade pitch angles $\alpha > 40°$ increases with a decrease in $\frac{a}{b}$, when one cannot compare the results of the calculation and experiment in the near-axial region also. Since

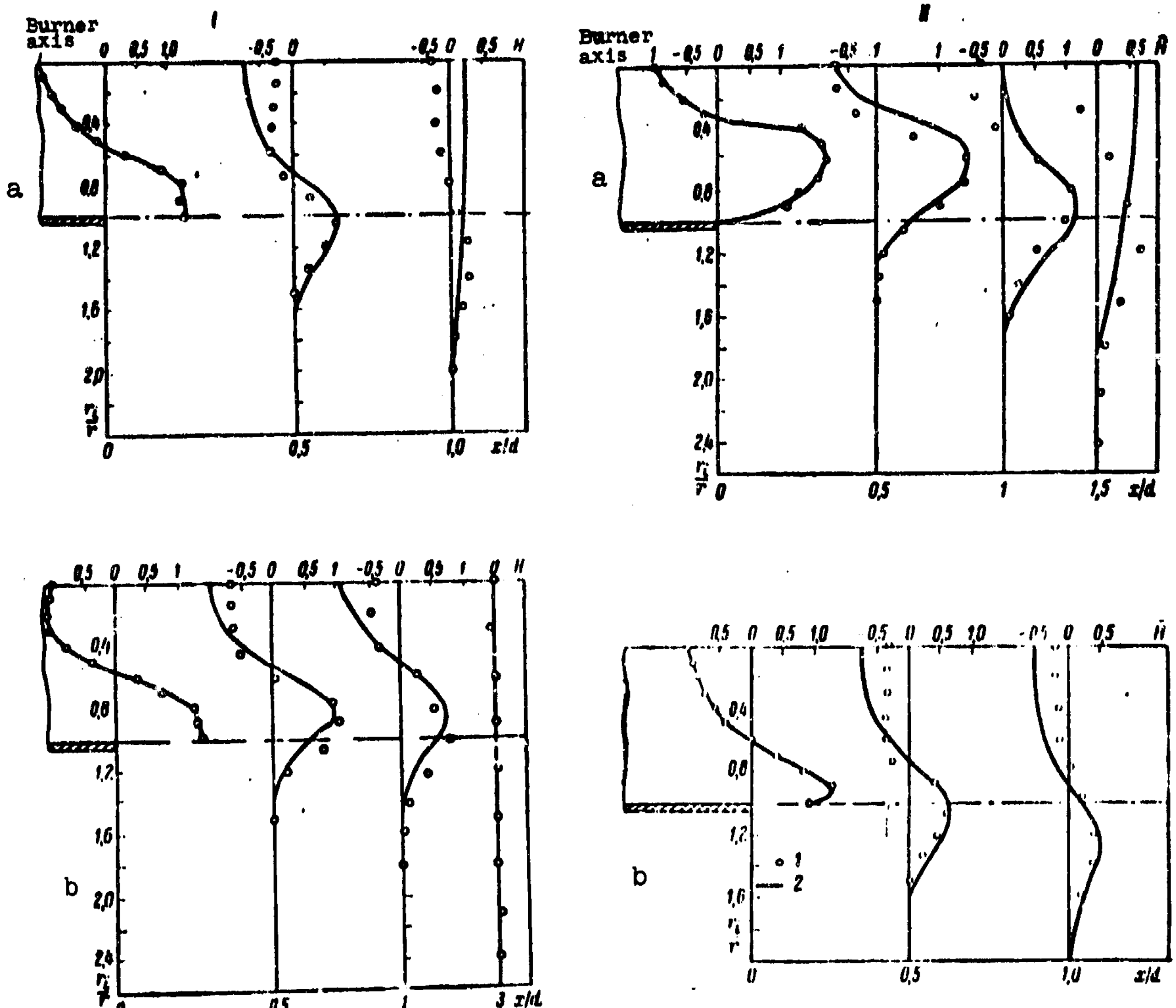

Figure 4. Field of total pulse H in a twisted jet flowing: I - from a helical swirl vane [$\frac{a}{b}$=0.25; n=1 (a), n=2 (b)]; II - from the axially tangential blade swirl vane [α=30°; β=25°, n=0.64 (a); β=45°, n=0.93 (b)]; 1 - test, 2 - theorectical data.

in work [5] $\frac{a}{b}$=0.90, while in our work $\frac{a}{b}$=0.25, the divergence in the results can be understood on the basis of these concepts.

An analysis of the data shown in Figures 2-4 showed that the calculation of the fields of total pulse H, according to the method of unequivalent problem, yields a satisfactory agreement

with a constant transverse coordinate $\eta = y$ on small twists of the air flow ($\alpha = 20$ and $30°$ in register A, $\frac{a}{b} = 0.25$, and $n = 1$ in register U). However, the calculation of a strongly twisted jet (beginning with angles $\alpha > 40°$ in register A when $\frac{a}{b} = 0.25$, and $n = 2$ in register U: at all angles α and β in register A B) requires the introduction of coordinate y into the theory of transformation. The inclusion of static pressure p_{CT} into the calculation scheme of the method should have taken into account the inverse flow of the fluid to the jet nucleus, since both the flow and rarefaction on the jet axis develop due to the centrifugal effect in the twisted jet. However, in the central portion of the jet we are unable to obtain an agreement between the calculation and test data; consequently, the introduction of value H instead of the dynamic pressure ρu^2 does not fully take into account strong inverse fluxes arising in a strongly twisted jet.

The calculation of the field of axial velocities in a twisted jet, according to the method of the equivalent problem of the theory of thermal conductivity, cannot be carried out without calculating the tangential velocity component, since the value of residual static pressure, included in $H = p_{CT} + \rho u^2$, must be determined by integrating the equation

$$\frac{\rho u_\varphi^2}{y} = \frac{dp_{CT}}{dy} \qquad (4)$$

according to the determined relationship $u_\phi(x, y)$.

As is known the tangential velocity in a twisted jet attenuates considerably faster than the axial velocity (for example, in the jet-source the axial velocity decreases with distance as $\frac{1}{x}$ and the tangential velocity - as $\frac{1}{x}2$). Therefore, the calculation methods which permit one to obtain a continuous deformation of the initial profile at small distances from the opening acquire a special importance in calculating the tangential velocity.

Work [5] purposes the use of the equation of thermal conductivity for value u_ϕ for calculating tangential velocity ρu_ϕ^2. The equation analogous to (1) is written for this equation

$$\frac{\partial(\rho u_\varphi^2)}{\partial \xi_\varphi} = \frac{\partial^2(\rho u_\varphi^2)}{\partial y^2} + \frac{1}{y}\frac{\partial(\rho u_\varphi^2)}{\partial y}, \qquad (5)$$

which is solved with the following initial and boundary conditions:

$$\begin{gathered} \xi_{\varphi\,(x=0)} = 0 \quad \rho u_\varphi^2 = f(y) \\ \xi_\varphi > 0 \left\{ \begin{array}{ll} y = 0 & \rho u_\varphi^2 = 0, \\ y \to \infty & \dfrac{\partial(\rho u_\varphi^2)}{\partial y} \to 0. \end{array} \right\} \end{gathered} \qquad (6)$$

Boundary condition $\rho u_\phi^2 = 0$, when $y=0$, is found to be in contradiction with the initial equation (5), although it is physically valid. Actually, when $y=0$ the solution for ρu_ϕ^2, similar to (2) transforms into

$$\rho u_\varphi^2(\xi_\varphi, 0) = \frac{1}{2\xi_\varphi}\int_0^\infty f(\rho)\, e^{-\rho^2/4\xi_\varphi}\rho\, d\rho \qquad (7)$$

and is never equal to 0.

Since with such a calculation system it is difficult to assign a boundary condition where $u_\phi = 0$ on the jet axis, in this work we purpose a new method for calculating the tangential velocity. The hypothesis lying at the base of this method consists of the following: the equation of diffusion is satisfied not by value ρu_ϕ^2, but by x which is the vector component of vortex $\frac{z}{x}$, determined by the formula

$$z_x = \frac{1}{y}\cdot\frac{\partial(u_\varphi y)}{\partial y}. \qquad (8)$$

In the hydrodynamics of a viscous laminar motion it is emphatically proven [4] that vortex z=curl v satisfies the non-stationary equation of thermal conductivity, which for the x-component of vortex z_x is written in the form:

$$\frac{\partial z_x}{\partial t} = \nu \Delta z_x, \tag{9}$$

where ν - viscosity; Δ - Laplace operator.

Proceeding from nonstationary equation of diffusion (9) to the equation of the method of the equivalent problem using the system usual for this method, we write the following equation for the x-component of the vortex

$$\frac{\partial z_x}{\partial \xi_x} = \frac{\partial^2 z_x}{\partial y^2} + \frac{1}{y}\cdot\frac{\partial z_x}{\partial y}. \tag{10}$$

The initial and boundary conditions for (10) are given in the form:

$$\begin{aligned} &\xi_x = 0 \quad (x = 0) \quad z = z_0(y); \\ &\xi_x > 0 \quad (x > 0) \quad z \to 0 \text{ when } y \to \infty. \end{aligned} \tag{11}$$

From the connection of z with u_ϕ, according to (8), it follows that now we can impose the necessary additional condition u_ϕ on $u_\phi/_{y=0}=0$. Actually, from (8)

$$u_\varphi = \frac{1}{y}\int_0^y zy\,dy. \tag{12}$$

When $y \to 0$

$$u_\varphi = \frac{1}{y} z(0)\, y^2 \Big|_{y\to 0} = z(0)\, y \Big|_{y\to 0} = 0.$$

Then the solution of equation (10) can be written in the form similar to (2):

$$u_{\varphi} = \frac{1}{2k_1 y} \int_0^y e^{-y^2/4k_1} y \left[\int_0^\infty z_0(r) e^{-r^2/4k_1} I_0\left(\frac{ry}{2k_1}\right) r\,dr \right] dy. \qquad (13)$$

The calculation of u_ϕ according to (13) is carried out numerically by approximating not the entire integrand function, but only the initial profile $z_0(r)$. This permitted us to reduce the problem of calculation of u_ϕ to calculating with the aid of the so-called P-functions (5). The calculation data and their comparison with the experiment for a jet flowing from the axial blade apparatus are shown in Figure 5. Profiles z were determined by the formula

$$z = \frac{1}{y} \cdot \frac{\partial (u_\varphi y)}{\partial y} = 2\omega + y \frac{\partial \omega}{\partial y} \quad \left(\omega = \frac{u_\varphi}{y}\right) \qquad (14)$$

based on the experimentally measured profiles of tangential velocity u_ϕ. It is evident from the figure that based on the proposed hypothesis the experimental data are described satisfactorily by the theoretical dependence.

The determination of vortex z by the experimental profiles u_ϕ in the opening, in a number of cases, leads to considerable errors. The second term $\left(y \frac{\partial \omega}{\partial y}\right)$ included in expression (14) introduces errors into the initial profile z(0), since angular velocity ω near the nozzle's edge drops sharply to 0 on a short segment of the transverse coordinate y. In those cases when ω near the nozzle's edge changes slowly (small slope angles of blades in a twisted jet) (Figure 6,a) the errors in profile z(0) are small. With large slope angles (α>40-45°), ω changes sharply near the nozzle's edge and the coincidence between the calculation and test worsens. To simplify the calculation of u_ϕ we attempted to apply a new method, not to the value of vortex z according to (14), but only to the value of angular

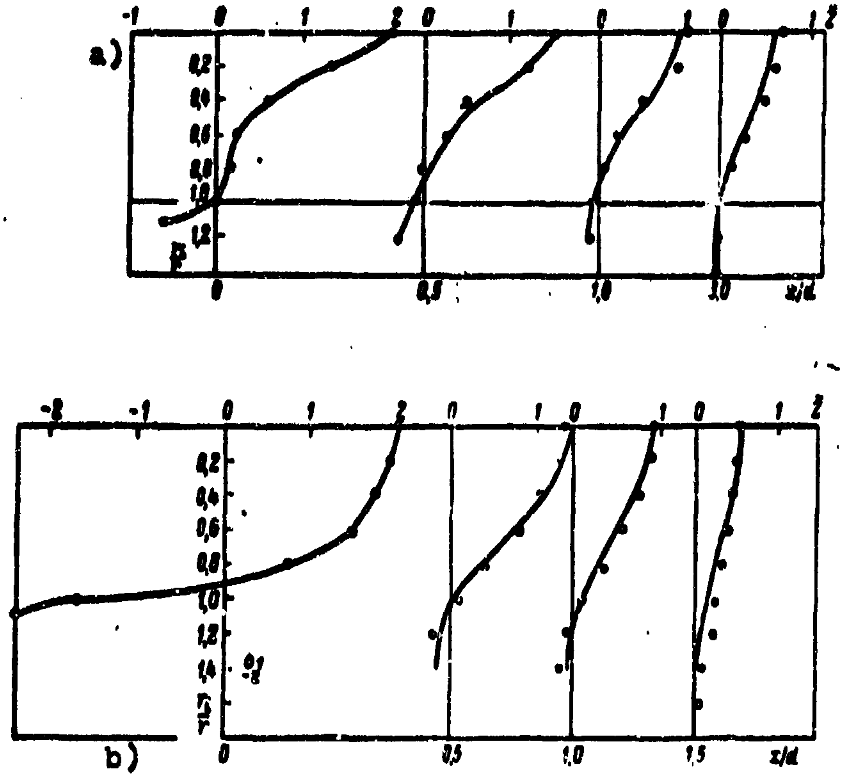

Figure 5. Field of the x-component of vortex z in a twisted jet. Values α, in degrees: a) 20, b) 40; 1 - test, 2 - theoretical data.

velocity $\omega = \frac{u_\phi}{y}$. All transverse profiles of tangential velocity were recalculated into the profiles of angular velocity according to this relationship. The initial profile of the latter was used in (2) to calculate the angular velocity in other sections. The calculation results are in good agreement with the experiment (see Figure 6). This method of calculation is not sufficiently strict, since ω is not a constant value; however $\int_0^\infty \omega\, y dy$ maintains a constant (with an accuracy up to 10-20%) value in all these sections. In practice, to find u_ϕ, using the angular velocity, is simpler and this method can be recommended for engineering calculations.

Dependence $\xi_\omega(a)$, necessary for the calculation is shown in Figure 7. From the fulfilment of equation (4) (the results of its experimental varification are shown in Figure 8) stems the

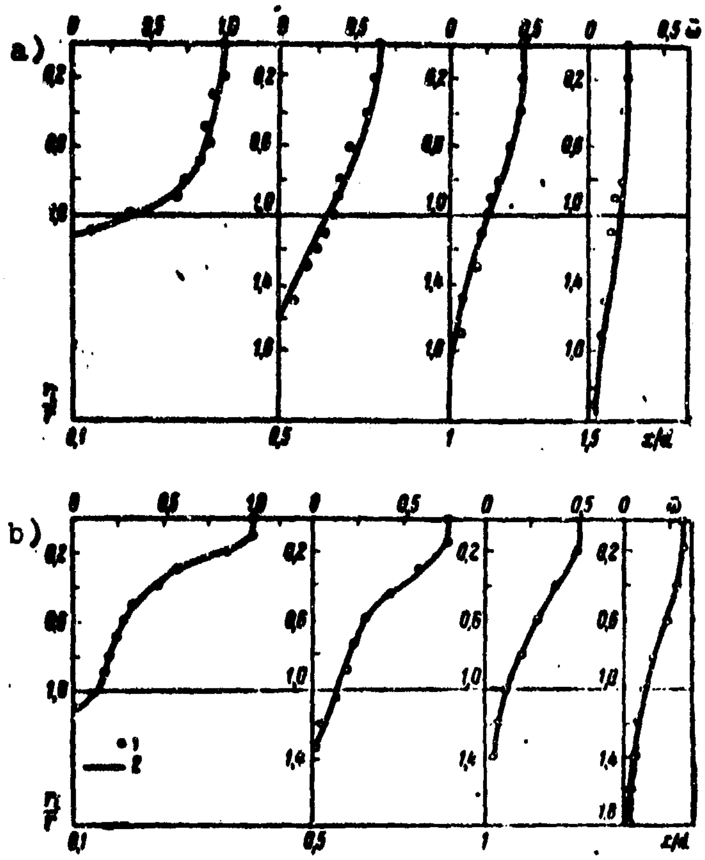

Figure 6. Field of angular velocity ω at the outlet from register A. Values α, in degrees: a) 40, b) 20; 1 - test, 2 - theoretical data.

possibility for calculating the field of static pressure p_{CT} in a twisted jet.

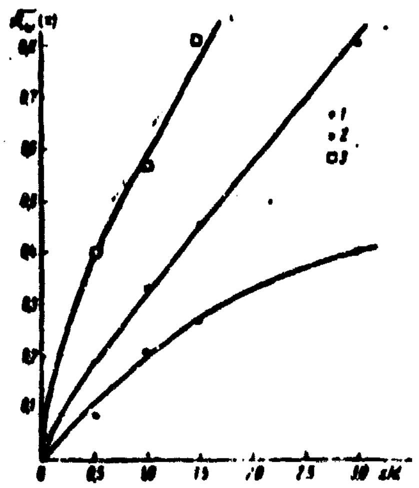

Figure 7. Dependence $\sqrt{\xi_w}(x)$ for a twisted jet from blade register A. Values α, in degrees: 1 - 20, 2 - 30, 3 - 40.

After calculating u_ϕ according to the proposed method and field H according to (2), it is possible to calculate the fields of the axial velocity component and to complete, in this manner, the

calculation of the principal aerodynamic characteristics of a twisted jet.

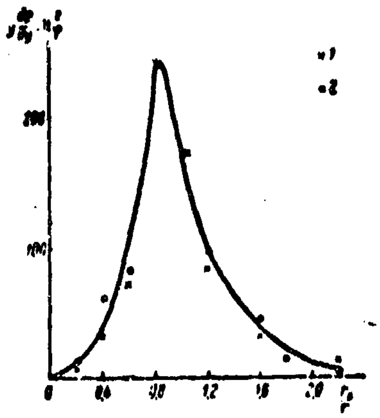

Fig. 8. Experimental varification of the equation (4) for a twisted jet flowing from register A with α=40° (section x=1.0).
$1 - y\frac{\partial p}{\partial y}$; $2 - u_{\phi}^{2}$.

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